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COLLECTIVE EXCITATIONS IN NEUTRON-DEFICIENT BARIUM, XENON, AND CERIUM ISOTOPES

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Abstract

The collective excitations of some neutron-deficient barium, xenon, and cerium isotopes have been studied with germanium counters. Various (heavy ion, xn) reactions have been used to produce ^{126}Ba, ^{124}Ba, ^{122}Xe, ^{120}Xe, and ^{134}Ce. The decay of ^{134}Pr to ^{134}Ce, with a half-life of 17 ± 2 minutes, was also studied. Partial level schemes for the ground-state rotational bands up to spin 8+ or 10+ are proposed for the nuclides investigated. The lifetime of the first-excited state in ^{126}Ba has been determined to be $2.7 \pm 0.5 \times 10^{-10}$ seconds and, hence gives the deformation of ^{126}Ba as $\beta = 0.24 \pm 0.02$.

The implications of the rotational energies and spacings as related to deformation in this region are discussed.

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1. Introduction

The existence of three regions in the periodic table where deformed nuclei exist is now well established. The properties of these nuclei have been surveyed by several authors[1,2]. Experimental evidence concerning a fourth region of deformation where N and Z both lie between 50 to 82 was first given by Sheline, Sikkeland, and Chanda[3]) who observed the first-excited states in ^{130}Ba, ^{128}Ba, and ^{126}Ba. These isotopes were subsequently studied by Chanda [4,5]), who proposed partial-level schemes for the three barium nuclei. The evidence suggesting that the nuclei in this region might be deformed consisted mainly of (1) systematics of the first-excited state energies, and (2) the ratio of the energy levels observed in relation to that expected for rotational bands in even-even deformed nuclei.

The study of the collective energy levels of nuclei in this new region of deformation is also the subject of the present work; in particular we have studied the levels of ^{126}Ba, ^{124}Ba, ^{122}Xe, ^{120}Xe, and ^{134}Ce. The systematic investigation of collective levels following radioactive decay is not always possible, so that other methods have been used in most of this work.

Several groups have observed the gamma rays from de-exciting nuclei produced in nuclear reactions. Morinaga and Gugelot [6]) first observed such gamma rays in the cascade to lower excited states of nuclei produced in (α,xn) reactions. Hansen, Elbek, Hagemann, and Hornyak [7]) used (p,xn) reactions and studied the spectra of the conversion electrons from various targets using a magnetic spectrometer. Stephens, Lark, and Diamond [8]), using (heavy ion,xn) reactions, observed the de-excitation cascades using an electron spectrometer

and also NaI(Tl) and germanium solid-state detectors. As shown in these works, the ground-state rotational band could always be seen up to the 6+ or 8+ level,

More recently several authors [9-11]) have reported studies using similar techniques. The work of Miyano et al. in observing the collective states in ^{130}Ba is of particular interest as it is in the neighborhood of the new region of deformation. This work verifies that of Chanda [5]) who used radiochemical techniques on ^{130}La to obtain the states in ^{130}Ba. The Miyano work also demonstrates the desirability of investigating more of the nuclei in this region with the "in-beam" technique.

2. Experimental Procedures

The Berkeley heavy-ion linear accelerator (Hilac) was used to accelerate beams of ^{14}N, ^{12}C, ^{11}B, and ^{10}B to the energies required to produce ^{126}Ba, ^{124}Ba, ^{122}Xe, ^{120}Xe, ^{134}Ce, and ^{134}Pr from the appropriate targets (table 1). The desired isotope's excitation function was calculated by using the Jackson Model [12]). The ion energy corresponding to the peak in the excitation function was used as a starting point to look for the desired product. A crude excitation function was then experimentally obtained by observing the products at various energies. In most cases the energy calculated from the Jackson Model for the peak of the excitation function and the value determined experimentally were within ±3 MeV. The bombarding energy given in table 1 is the one which gave the cleanest spectrum of the desired reaction product. In the case of ^{124}Ba and ^{122}Xe, two different reactions were employed, using different projectiles and targets.

2.1. IN-BEAM BOMBARDMENT METHODS

The experimental setup for the in-beam gamma-ray detection (fig. 1) consisted of: (a) a retractable gold scatter foil and a beam-energy detector for beam-energy measurements, (b) a collimator of approximately 3/8-in. diameter connected to an electrometer which measured the beam hitting the collimator and facilitated focusing of the beam, (c) the target assembly which included the target on a retractable paddle and lucite windows which allowed viewing the target while in the beam location, (d) the Faraday cup, connected to an electrometer which measured the beam intensity, and (e) the lithium-drifted germanium counter which was usually placed a few millimeters from the lucite window at 90 deg. to the beam direction.

Since the Hilac "partial-energy" beam was used, no degradation of the beam by absorbers was necessary. The desired energy was achieved by changing the tilt of the gradient in the post-stripper tank, and adjusting the tank tuners. The beam was magnetically analyzed by deflection through 52°, and then traveled through a quadrupole focusing magnet into the experimental area. The beam-energy was measured by scattering the beam from a thin (~1 mg/cm^2) gold foil into a solid-state detector which was at an angle of 20° to the beam. The detector was calibrated with the full-energy beam (10.4±0.2) MeV/nucleon [13]) and the beam energy measured was considered accurate to within 1-2%. The ratio of the beam hitting the Faraday cup to that hitting the Collimator in front of the target was used as an aid in final focusing of the beam. This ratio was generally 2:1 or better; although it did at times go as low as 1:2. The average beam currents were held to a few nA when using the Li-drifted germanium counter to detect the gamma rays.

Table 1. Nuclear reactions employed.

Isotope	Reaction	Approx. Heavy Ion Bombarding Energy (MeV)
^{126}Ba	$^{115}In(^{14}N, 3n)^{126}Ba$	52
^{124}Ba	$^{115}In(^{14}N, 5n)^{124}Ba$	84
	$^{116}Sn(^{12}C, 4n)^{124}Ba$	80
^{122}Xe	$^{115}In(^{10}B, 3n)^{122}Xe$	37
	$^{115}In(^{11}B, 4n)^{122}Xe$	57
^{120}Xe	$^{115}In(^{10}B, 5n)^{120}Xe$	67
^{134}Ce	$^{127}I(^{11}B, 4n)^{134}Ce$	57
^{134}Pr	$^{127}I(^{12}C, 5n)^{134}Pr$	90

The beam-pulse repetition rate was twelve pulses per second in the early part of this work, and was later increased to forty pulses per second. The beam-pulse length was ~3 milliseconds.

The targets used were of two types: (1) thin self-supporting targets, and (2) thick targets. Thin (about 5 mg/cm^2) self-supporting metallic targets of indium and separated tin isotope were used in the gamma-ray apparatus as previously described (see fig. 1). Thick targets of indium and lead iodide were used in a terminating target holder, where the target holder itself served as the Faraday cup. The thick targets were: 0.003-in. thick indium foil targets, and approximately 20 mg/cm^2 lead iodide powder which served as an iodine target. The lead iodide target was made by pressing the powdered lead iodide into a flat disk and then spraying it with an acrylic lacquer to form a support for the pressed powder.

2.2. LIFETIME MEASUREMENT PROCEDURE

The method used for measuring the lifetime of the first-excited state of ^{126}Ba was essentially that of Novakov, Hollander, and Graham [14]). The equipment was set up by Burde, Diamond, and Stephens and made use of a small wedge-gap electron spectrometer. The diagram of the high-voltage target arrangement is shown in fig. 2. As the reaction products are made, they are given a recoil energy around 5 MeV. Conversion electrons are given off before the recoiling nuclei reach the negative high-voltage grid, which is placed at a distance depending on the mean lifetime of the level. The electrons are then slowed down by the negative-voltage gradient an amount depending on their distance of emission

from the grid. After passing the grid, the electrons are accelerated by the full-voltage gradient to an energy greater than their original energy. In this manner an electron is given an additional amount of energy, the magnitude of which depends on the recoil distance before electron emission, and therefore on the lifetime of the nuclear state involved. By comparing the electron energy with the high voltage off to that when it is on, and knowing the recoil velocity and applied voltage, one can obtain the mean lifetime of the state. To obtain a reference peak position, the negative voltage was applied only to every other Hilac pulse; thus by storing the information separately, a perturbed and unperturbed peak were recorded during the same magnet sweep. Target thickness of ~200 $\mu gm/cm^2$ were used. A description of the calculations and uncertainties involved has been given elsewhere [15].

2.3. RADIOCHEMICAL STUDY OF ^{134}Pr DECAY

In studying the energy levels of ^{134}Ce, radiochemical separation and study of the radioactive decay of ^{134}Pr were employed as well as the in-beam technique. The former procedure was similar to that used by Chanda [5]. The copper iodide target was prepared by evaporating the copper iodide in vacuum and depositing it on 2.7 mg/cm^2 nickel foil. Target thickness varied between 1 and 2 mg/cm^2. A beam of carbon ions, with a beam current of around 150 nA, was used. The praseodymium nuclei produced were chemically separated from the other products present. A crude excitation function was measured, and ^{134}Pr was produced with maximum yield by selecting the beam energy as ~90 MeV. A detailed description of the procedures used here has been given elsewhere [15].

3. Results

The mass assignments of the nuclei considered in this work were based on several criteria. The peak of the calculated excitation function for a product formed in a given reaction was used as a starting point for investigation of the nuclides studied. The assignment of the gamma-rays from ^{126}Ba and ^{122}Xe was in agreement with the values previously found by Chanda [4]) (^{126}Ba) and Morinaga and Lark [16]) (^{122}Xe). The results of the ^{134}Pr radiochemical study and the in-beam method both support the assignment of the ^{134}Ce levels. Since ^{124}Ba was produced by two reactions, with different targets and projectiles, both giving the same transitions, this mass assignment is likewise considered to be quite certain.

The spin and parity assignments were made from the systematic behavior of the observed lines. This includes (1) the regular spacing of the transition energies, approaching in some cases the I(I+1) rotational spacing, (2) the outstanding intensity of the lines which decreased monotonically with increasing transition energy, and (3) the knowledge that in all cases where the spins and parities were known, the ground-state rotational band was the most prominent (or only) band populated by the method used. In the case of ^{126}Ba, the E2 assignment for the lowest energy transition was also supported by its lifetime and the measured K/L intensity ratio.

The germanium counter was calibrated by the use of several gamma-ray standards. The ^{177}Lu^{m} standard used in the 0-500 keV range is an exceptionally good standard since it has over 20 transitions or peaks easily resolved with these counters [17,18]). The use of ^{177}Lu^{m} and other standards enabled us to measure the gamma-ray energies to an accuracy of ±1 keV.

In the rest of this section the nuclides will be discussed individually. Section 4 will summarize the data and discuss their interpretation.

3.1 BARIUM-126

The gamma-ray spectrum as found near the peak of the $^{115}In(^{14}N,3n)$ excitation function is shown in fig. 3. The relative intensities of the first four transitions of ^{126}Ba as observed were 1.00:0.65:0.47:0.26 (after correction for absorbers and detector efficiency). In addition to the transitions that have been assigned to ^{126}Ba, three other peaks were found. The 511-keV annihilation radiation peak, the 560-keV ^{115}In Coulomb excitation peak, and a 690-keV peak can be seen. The 690-keV peak is observed in all Li-drifted germanium counter spectra when fast neutrons are present, and results from a $^{72}Ge(n,n')^{72}Ge^{*}$ reaction. The partial-level scheme involving the ground-state rotational band is shown in fig. 4.

The K/L ratio of the 256-keV level was measured to be 4.5±0.6, and while agreement with the theoretical value for an E2 transition is not exact (K/L = 5.4), the transition has been so assigned. (The theoretical K/L ratio for an M1 transition of this energy would be 7.5.)

An example of the electron spectra observed in the lifetime study of the first-excited state of ^{126}Ba is shown in Fig. 5. The mean lifetime (τ) for the 256-keV transition was $2.7 \pm 0.5 \times 10^{-10}$ seconds. The limits of error quoted are due mainly to the statistical uncertainty in the calculation of the centroids of the peaks in the electron distributions. (In determining the lifetime of the

2+ level, an approximate upper limit for the lifetime of the 455-keV 4+ transition was also measured. This value, $\leq 8 \times 10^{-11}$ seconds, has been subtracted from $2 \rightarrow 0$ lifetime to allow for the effect of the decay from the $4 \rightarrow 2$ level.) Figure 6 shows the measured lifetime value for the 256-keV transition along with values for some other nuclei. This figure follows that of Grodzins [19]. The value for the lifetime as determined above gives a deformation (β) of ^{126}Ba of 0.24±0.02, where β is the deformation parameter of a spheroid given by $\beta = 4/3(\pi/5)^{\frac{1}{2}}(\Delta R/R_o)$ with R_o the mean nuclear radius and ΔR the difference between the major and minor semi-axis of the spheroid. Unfortunately the experiment does not distinguish between an rms value of β resulting from oscillations about a spherical shape and a stable equilibrium value of β.

3.2 BARIUM-124

Of the five nuclei considered in this work, ^{124}Ba has the least reliable assignments of gamma rays in its decay. It was produced in ^{115}In(^{14}N,5n), and ^{116}Sn(^{12}C,4n) reactions, and the background in these cases was much higher than for ^{126}Ba which was formed in an ^{115}In(^{14}N,3n) reaction. The maximum yield of ^{124}Ba occurs at higher bombarding energies where more reactions are possible. The products from these reactions all contribute to the background. Of these products, those formed in (^{14}N,αxn) and (^{12}C,αxn) reactions may become useful in future study of this region.

The 229-keV gamma ray was assigned as the $2 \rightarrow 0$ transition of ^{124}Ba. As can be seen in the ^{116}Sn(^{12}C,4n) spectrum shown in fig. 7, there is also a prominent 189-keV peak in the spectrum. This peak was also present in the

$^{115}In(^{14}N,5n)$ reaction. It appears to follow the excitation function with the other peaks which have been identified as ^{124}Ba transitions although this determination was crude enough to leave some question. However, from a preliminary lifetime measurement, the 189-keV lifetime appeared to be about an order of magnitude longer than the 229-keV transition and unreasonably long for a collective E2 transition of this energy. On the basis of this and the systematic variation of the energies of the first-excited states of the barium nuclei, the 229-keV transition was assigned as the $2 \rightarrow 0$ transition. It is hoped that future investigation on this nuclide will allow placement of the 189-keV transition. Figure 4 gives the partial-energy level diagram for ^{124}Ba.

3.3 XENON-122

The spectrum as found in the $^{115}In(^{11}B,4n)$ reaction is shown in fig. 8. While the background for this reaction is higher than for the $^{115}In(^{10}B,3n)$ reaction, the peaks found are essentially the same. The five transitions identified with ^{122}Xe are the most prominent; however, there is a peak at 460 keV which did not follow the same excitation function as the other peaks. This peak seems to be due to ^{123}Xe, and did not appear in the $(^{10}B,3n)$ reaction to any extent. For $^{115}In(^{11}B,4n)$ the 819-keV assignment is complicated by several peaks (see fig. 8); assignment was made by comparing with the $^{115}In(^{10}B,3n)$ peaks. The relative intensities of the first four transitions, after correction for absorbers and counter efficiency was 1.00:0.87:0.86:0.74 in ^{122}Xe.

Morinaga and Lark[16]) also studied the levels of ^{122}Xe using the ^{122}Te(α,4n) reaction and NaI(Tl) counters. The agreement of the two works is good. The partial level decay scheme as determined by the present work is shown in fig. 9.

3.4 XENON-120

The first three transitions of the ground-state rotational band found in the ^{115}In(^{10}B,5n)^{120}Xe reaction were assigned without ambiguity (fig. 10). They are very prominent and easily identified by their excitation functions and systematic spacing. The next two peaks in the band were not assigned, however, with the same assurance and are shown as dashed in the level scheme in fig. 9.

3.5 CERIUM-134

The spectrum obtained with the in-beam technique in the ^{127}I(^{11}B,4n) reaction is shown in fig. 11. The ^{127}I(^{10}B,3n) reaction was also investigated but the Coulomb excitation of ^{127}I dominated the spectrum at the energies necessary for the 3n reaction.

The assignment of the first two peaks agrees well with the radiochemical experiment. The 815-keV peak has been assigned as the 6 → 4 transition. The 871-keV peak was tentatively assigned as the 8 → 6 transition, while the peak at 840 keV was not assigned. The 871-keV peak was chosen on the basis of the systematic spacings involved. Figure 12 shows the partial energy-level scheme for ^{134}Ce.

4. Discussion of Results

A summary of the ground-state rotational band transitions as determined in this work is shown in Table II. The classification system of the transitions has the following meanings: A, definite peak, definite assignment; B, definite peak, rather indefinite assignment; and C, indefinite peak and indefinite assignment. The nuclei studied in this work are probably at the edge of a region of deformation, and hence the transitions and deformation determined in this work are of interest in extending the knowledge of nuclear shapes in this region.

It must be pointed out in the beginning that no sharp discontinuity of nuclear properties occurs in this region (such as is found in the region above the 82 neutron shell) which would indicate the definite onset of stable equilibrium deformations in the ground states of nuclei. Furthermore, it has been pointed out that the existence of a stable equilibrium deformation cannot be established from a knowledge of the energy of the first 2+ state and its E2 transition probability to the ground state (rms value of β) alone. Thus, to make definite statements concerning nuclear shapes, one would have to know considerably more about higher collective (vibrational) excitations. In the absence of such information, we can only compare the ground-state band properties of these nuclei with those of other nuclei, lying in regions of the periodic table where there is more knowledge about the nuclear shapes. This has been done in previous studies of this region, and we will present briefly the extension of these comparisons to the present data. However, it is our point of view that the best estimate of the shape of a particular nucleus can be made from the comparison of <u>all</u> the data for that nucleus with comparable data for other nuclei. This comparison will be presented at the end of this section.

Table II. Ground-state rotational band transitions* (keV).

Transition	^{120}Xe	^{122}Xe	^{124}Ba	^{126}Ba	^{134}Ce
2 → 0	321.8 A	331.1 A	229.5 A	256. 1 A	409.5 A
4 → 2	472.6 A	497.5 A	420.6 A	455. 5 A	638.9 A
6 → 4	601.4 A	638.2 A	573 B	621.4 A	814.6 A
8 → 6	701 C	749.9 A	634 C	757.1 A	871.4 B
10 → 8	773 C	819 B		829 C	

*The accuracy of these transitions is expected to be ± 1 keV.

In stating the evidence for a new region of deformation with less than 82 neutrons, Chanda[4,5]) used several methods to estimate the deformation of the barium nuclei from the energy levels involved. Two of these methods are: (1) the comparison of the first-excited state energies E_{2+} with an $(E_{2+})_{crit}$ as suggested by Alder et al.[20]) and (2) comparison of the observed E_4/E_2, E_6/E_2, etc., ratios with those expected from the rotational model. The energy of the first-excited state of the even-even xenon, barium, and cerium isotopes is shown in fig. 13. To obtain a rough indication of the transition between rotational and vibrational nuclei, the energy of the first-excited state is compared to the above-mentioned critical value[20]) given as:

$$(E_{2+})_{crit} = \frac{3\hbar^2}{0.23\,\mathfrak{J}_{rig}} \qquad (1)$$

where $\mathfrak{J}_{rig}$ is the moment of inertia of a rigid rotator. If $E_{2+} < (E_{2+})_{crit}$, the implication is that the nuclei might be deformed and rotational spectra could occur. The first-excited states of ^{126}Ba and ^{124}Ba lie below the value of $(E_{2+})_{crit}$ as can be seen in fig. 13. It seems clear, however, that this does not indicate anything more specific about these nuclei than that they lie in a region where stable equilibrium deformations are plausible.

For even-even nuclei the ground-state rotational-band energy levels are fairly well described using the rotational formula:

$$E_I = \frac{\hbar^2}{2\mathfrak{J}} I(I+1) \qquad (2)$$

where I represents the spin of the state, and $\mathfrak{J}$ is the moment of inertia, and only even spin states and positive parity are allowed. Equation (2) predicts the energy ratios:

$$E_4/E_2 = 3.33;\ E_6/E_2 = 7.00;\ \text{etc.}$$

Figure 14 shows the energy level ratios E_I/E_2 (ratio of the energy of the state with spin I to the energy of the first-excited 2+ level) for typical nuclei in the other regions and the nuclides of this work. The rise in the rare-earth and heavy-element regions to values near the above predicted ones are regarded as an indication of deformation in these regions. A rise can also be seen for the nuclei just below 82 neutrons; however the rotational values are not very closely approached. This does not seem to cast very much light on the question of stable deformations of ground states in this region.

As seen in the comparison of E_{2+} with $(E_{2+})_{crit}$ and the ratio E_I/E_{2+}, the more neutron-deficient barium isotopes studied seem to have the largest probability of stable deformation. The value for the quantity E_I/E_{2+} for ^{120}Xe, as determined in this work, is lower than that for ^{122}Xe and, therefore, the deformation (or tendency toward deformation) of the xenon isotopes may have reached a maximum with ^{122}Xe. The more neutron-deficient isotopes of cerium, on the other hand, will probably have still larger (tendency toward) deformations, and may well exceed those of the barium isotopes.

The lifetime for the first state in ^{126}Ba can also be used to calculate the enhancement factor, F, for this transition. The enhancement factor is:

$$F = \frac{T_\gamma(\text{experimental})}{T_\gamma(\text{s.p.},\ 2 \rightarrow 0)} \tag{3}$$

where the single proton transition probability, T_γ, is given by[19]):

$$T_\gamma(\text{s.p.},\ 2 \rightarrow 0) = 7.5 \times 10^7\ E_\gamma^5(2 \rightarrow 0)A^{4/3} \tag{4}$$

with $E_\gamma(2 \rightarrow 0)$ in MeV, T_γ is in sec^{-1}, A is the mass number, the statistical factor has been set equal to one, and the nuclear radii have been assumed to vary as $r = 1.2\ A^{1/3}$ fm. For the $2 \rightarrow 0$ transition in ^{126}Ba, $F \cong 70$, a value which again is intermediate between deformed and spherical nuclei.

In fig. 15 is shown the most complete comparison we could construct of the information on three of the presently studied nuclei with nuclei from other regions. Here we have plotted the rotational constant, A_I, (as defined from the transition energies) for <u>all</u> the known rotational (or vibrational) levels in the various nuclei as a function of the spin of the upper level. In an attempt to remove the mass dependence of the energies, all were normalized to A = 170 assuming an inverse $A^{5/3}$ dependence of the energies on mass number. That this is useful is empirically evident from the rather close grouping at higher spins of levels from known rotational nuclei having masses ranging from 156 to 238. Whether or not there is physical significance to this grouping at high spins is not clear, and we do not wish to pursue that point here. Our intent here is rather to show that an empirically useful normalization for mass number is achieved, and comparison of the presently studied nuclei with others is thus facilitated.

In fig. 15 the height of a point is related to the energy difference between successive levels (transition energy), and the slope of the line connecting two points is related to the ratio of successive transition energies. Thus from the plot one can compare both of these quantities for various nuclei. The plot is so constructed that a perfect rotor would give a horizontal line. It is clear from fig. 15 that at low spins the barium and xenon nuclei lie above those nuclei which one is essentially certain have stable equilibrium deformations in their ground states (the ^{164}Dy - ^{156}Dy group). On the other hand they lie clearly below those which are not deformed in their ground states (the ^{188}Pt - ^{190}Hg group). In fact, they are comparable in initial height with the osmium and light platinum nuclei. When higher spin states are considered, however, it is apparent that the Ba and Xe nuclei are very much like ^{184}Pt and not like the Os nuclei. The main characteristics of the heavier Os nuclei are likely to be: low γ-vibrational bands, the heaviest ones possibly being γ-unstable; but high β-vibrational bands and very likely stable equilibrium deformations. On the other hand the light Pt nuclei have very low β-vibrational bands, with stable equilibrium deformations in the ground state uncertain; but higher γ-vibrational energies than in the heavier Os nuclei, suggesting a clear preference for axially-symmetric (probably prolate) shapes. The Ba and Xe nuclei are presumably like the light platinum nuclei above, a conclusion which is supported by the similarity in shape (but not height) between ^{126}Ba and ^{156}Dy. The ^{156}Dy nucleus is almost certainly like the light platinum nuclei, except that it is reasonably clearly deformed in its ground state, and correspondingly is lower in height in fig. 15.

Nuclei such as ^{184}Pt and the light Ba and Xe nuclei studied here, must be quite soft toward deformation (low β-vibration) and are likely to be stretched

under rotation to become deformed nuclei. This is indicated in fig. 15 by their rapid drop with increasing spin to the region of the clearly rotational nuclei. Whether they are deformed in their ground states is not really clear, however, even for ^{184}Pt where ground, β, and γ bands all appear to be known. To decide this point on the basis of the present data one would have to carry out model calculations of the type done by Kumar and Beranger[21]), and when the known characteristics of the levels are reproduced, the ground state wavefunction can be examined. Perhaps other experimental indications of the ground state shape can be found; however, this is not so easy if one does not assume that the shapes of the ground and lowest 2+ states are necessarily the same.

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21) K. Kumar and M. Baranger, to be published; K. Kumar, Lawrence Radiation Laboratory Report, UCRL-16768 (1966); K. Kumar, Michigan State University Technical Report, MSPT-101 (1966)

Figure Captions

Fig. 1. Vertical cross-section of the experimental setup for gamma-ray detection.

Fig. 2. Drawing of the target-high voltage assembly used to measure the lifetime of the first-excited state of ^{126}Ba. The distance c could be varied, while the distance b was fixed.

Fig. 3. Pulse-height spectrum of ^{126}Ba as observed from an ^{115}In target bombarded by 52 MeV ^{14}N ions.

Fig. 4. The partial level scheme of barium isotopes as found in this work.

Fig. 5. The electron spectra in the region of the K line of the 256 keV transitions from an ^{115}In target bombarded with 52 MeV ^{14}N as found using the lifetime apparatus.

Fig. 6. Reciprocal transition probability T_{γ}^{-1} $(2 \rightarrow 0) = \tau_{\gamma}$ as a function of energy, E_{2+}. The solid point represents the value determined in the present work. The open circle values are from ref. 19.

Fig. 7. Pulse-height spectrum of ^{124}Ba as observed from a ^{116}Sn target bombarded with 80 MeV ^{12}C ions.

Fig. 8. Pulse-height spectrum of ^{122}Xe as observed from an ^{115}In target bombarded with 57 MeV ^{11}B ions.

Fig. 9. The partial level schemes of xenon isotopes as found in this work.

Fig. 10. Pulse-height spectrum of ^{120}Xe as observed from an ^{115}In target bombarded with 67 MeV ^{10}B ions.

Fig. 11. Pulse-height spectrum of ^{134}Ce as observed from an ^{127}I target bombarded with 57 MeV ^{11}B ions.

Fig. 12. Partial level scheme for ^{134}Ce.

Fig. 13. The energy of the first-excited states of the even-even xenon, barium, and cerium isotopes. The $(E_{2+})_{crit}$ shown as the dashed line indicates the estimated region of transition between spherical and spheroidal nuclei. (The ^{132}Ce point is an approximate value as observed in the ^{127}I (^{12}C,7n) reaction.

Fig. 14. The energy ratio E_I/E_{2+} of the even-even nuclei represented. The neutron closed-shells are indicated by the vertical dashed lines; the Bohr-Mottelson theoretical limits are shown as horizontal dashed lines. The data has been given in ref. 5.

Fig. 15. The rotational constant, A_I, defined from the transition energy is plotted versus the spin, I, for a variety of nuclei including three from this work. All the nuclei were normalized to mass 170 by assuming an inverse $A^{5/3}$ dependence of the energies on mass number.

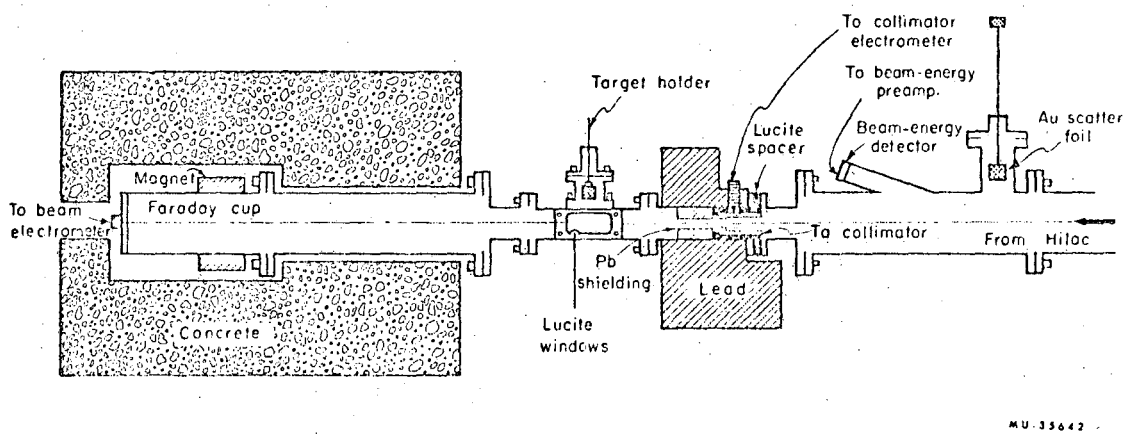

To collimator electrometer
To beam-energy preamp.
Target holder
Lucite spacer
Beam-energy detector
Au scatter foil
Magnet
To beam electrometer
Faraday cup
To collimator
From Hilac
Pb shielding
Lead
Lucite windows
Concrete
MU-35642

Fig. 1

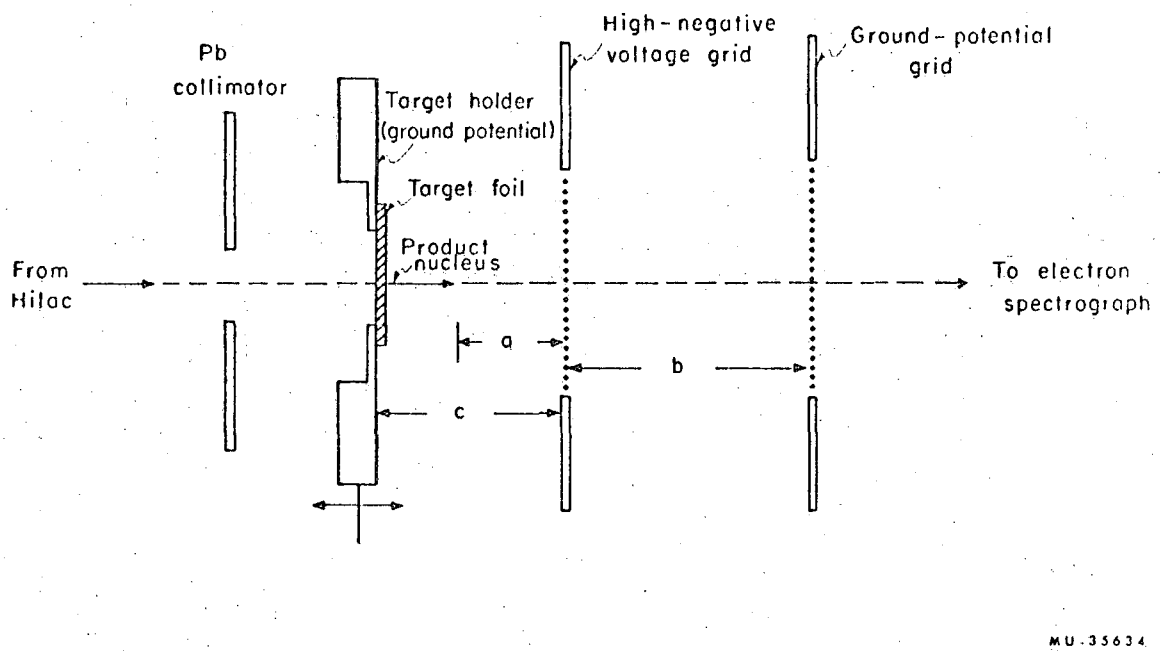

Pb
collimator
Target holder
(ground potential)
Target foil
Product
nucleus
From
Hilac
High-negative
voltage grid
Ground-potential
grid
To electron
spectrograph
a
b
c
MU-35634

Fig. 2

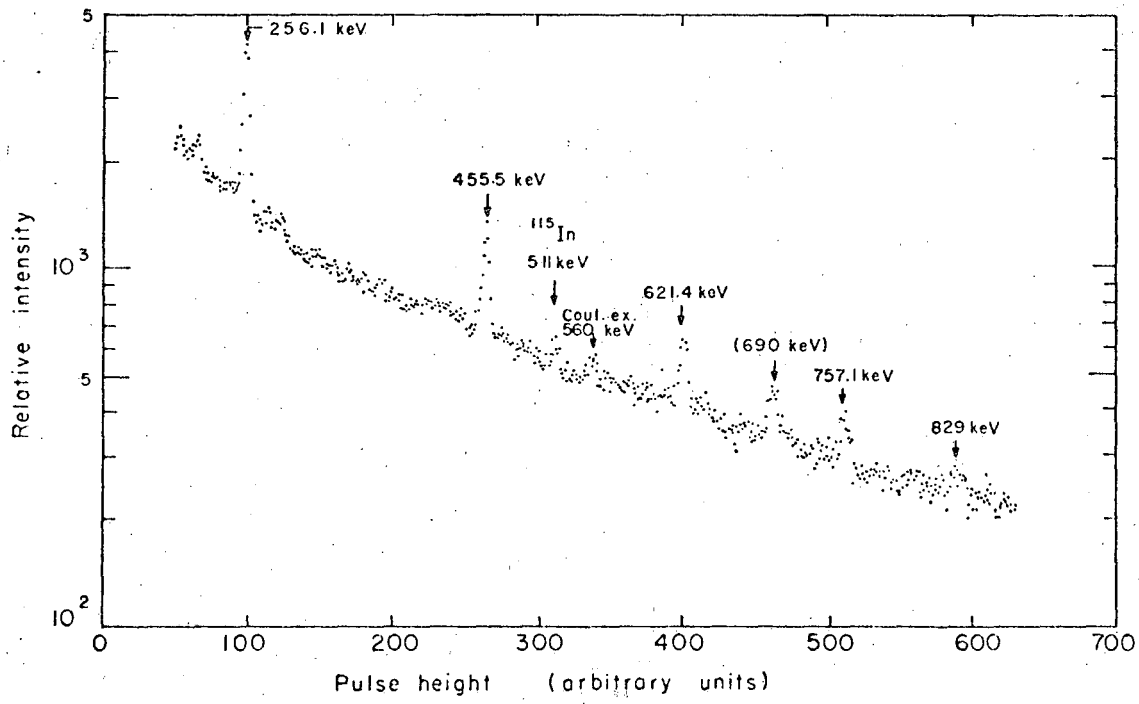
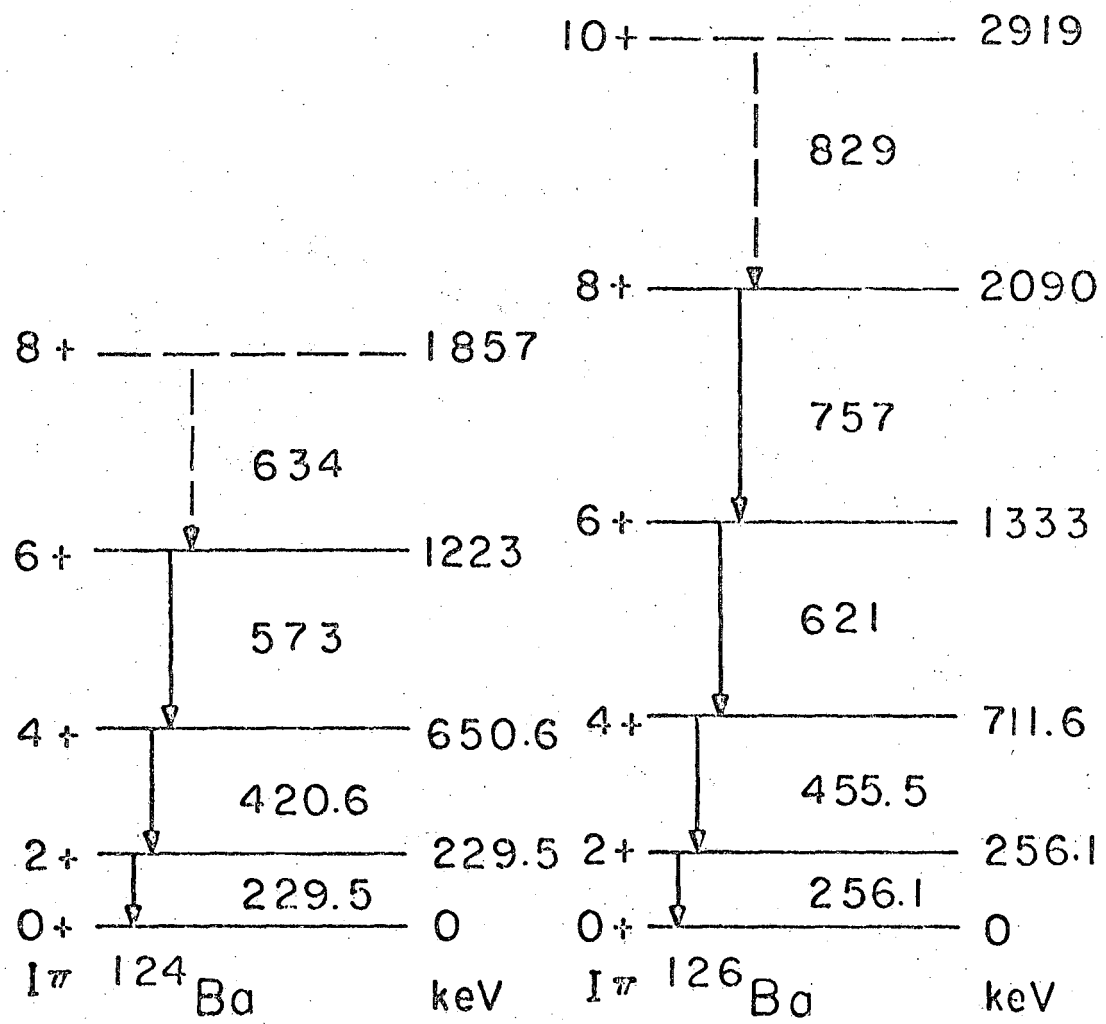
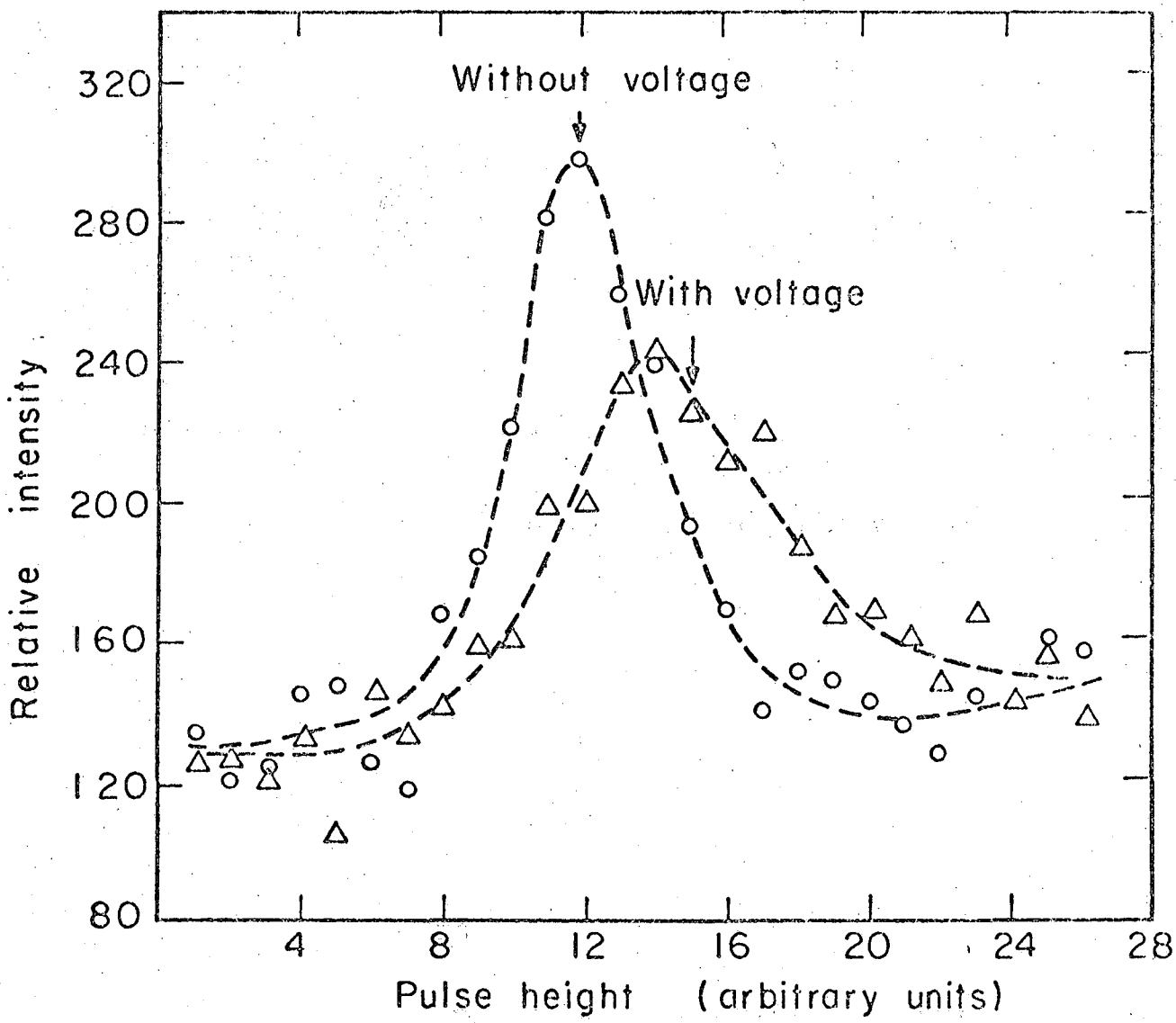

256.1 keV
455.5 keV
115In
511 keV
Coul. ex.
560 keV
621.4 keV
(690 keV)
757.1 keV
829 keV
Relative intensity
Pulse height (arbitrary units)
5
10^3
5
10^2
0
100
200
300
400
500
600
700

Fig. 3



MU-35629

Fig. 4



MU-35628

Fig. 5

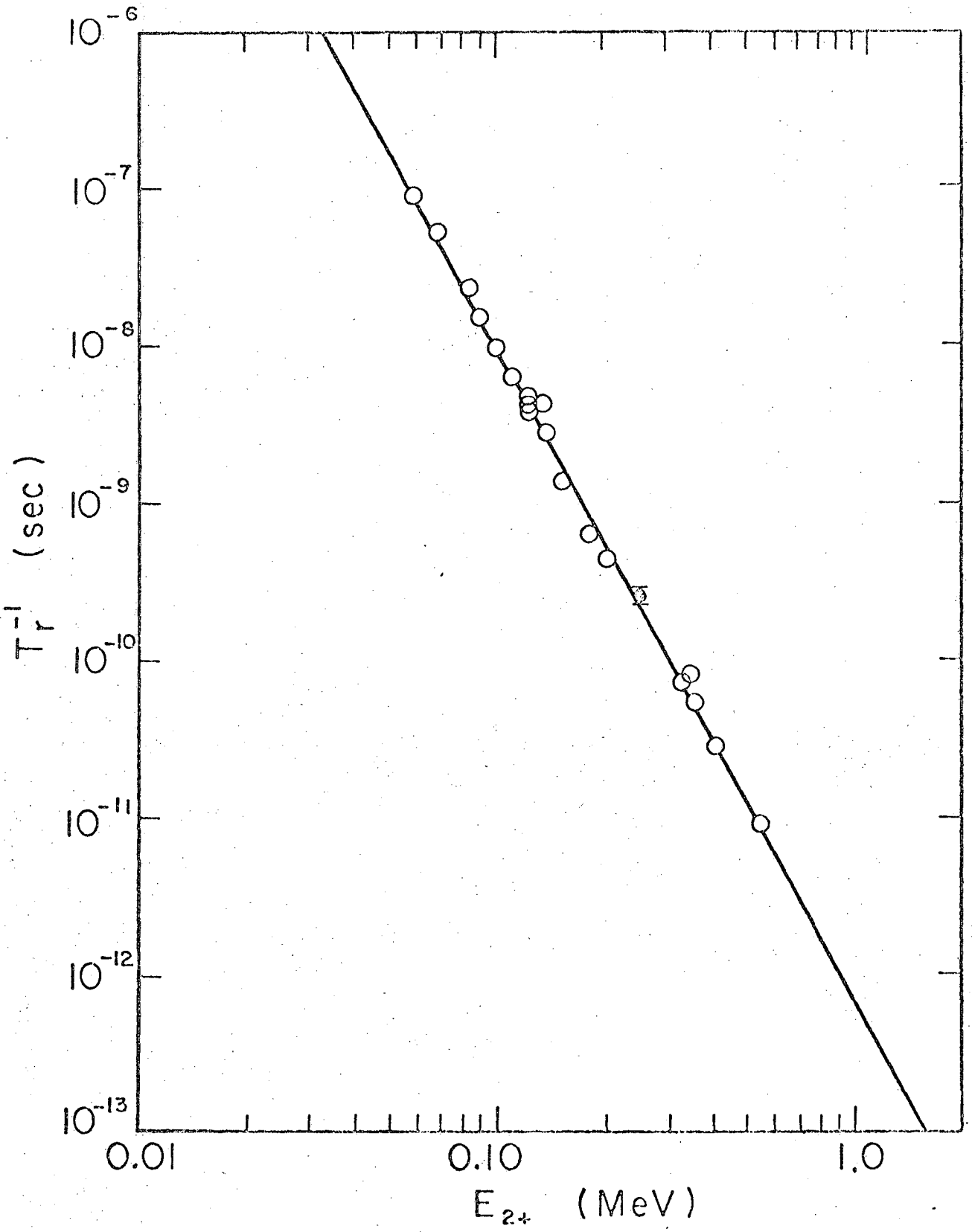
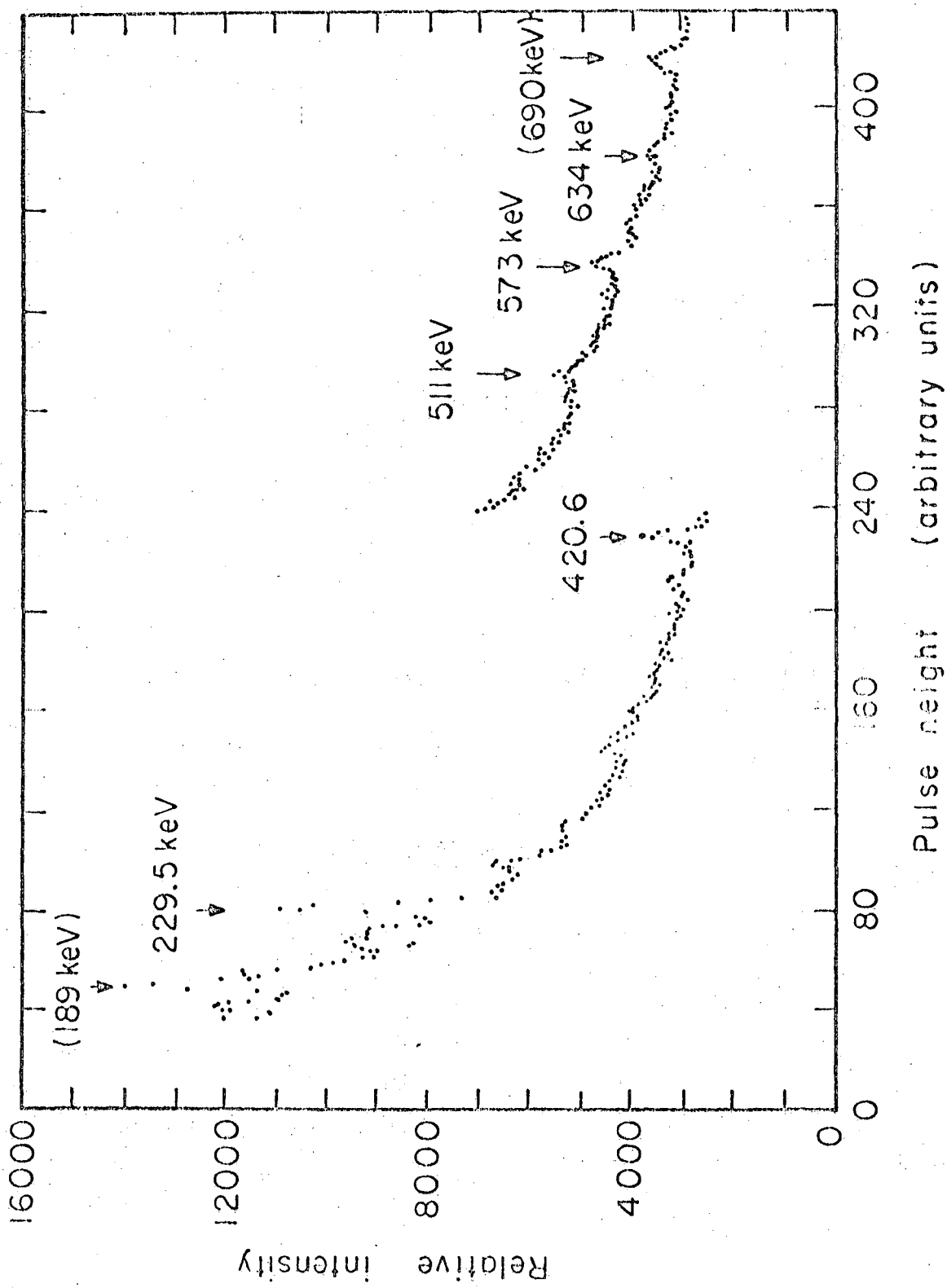


Fig. 6

MU-35625



MU-35635

Fig. 7

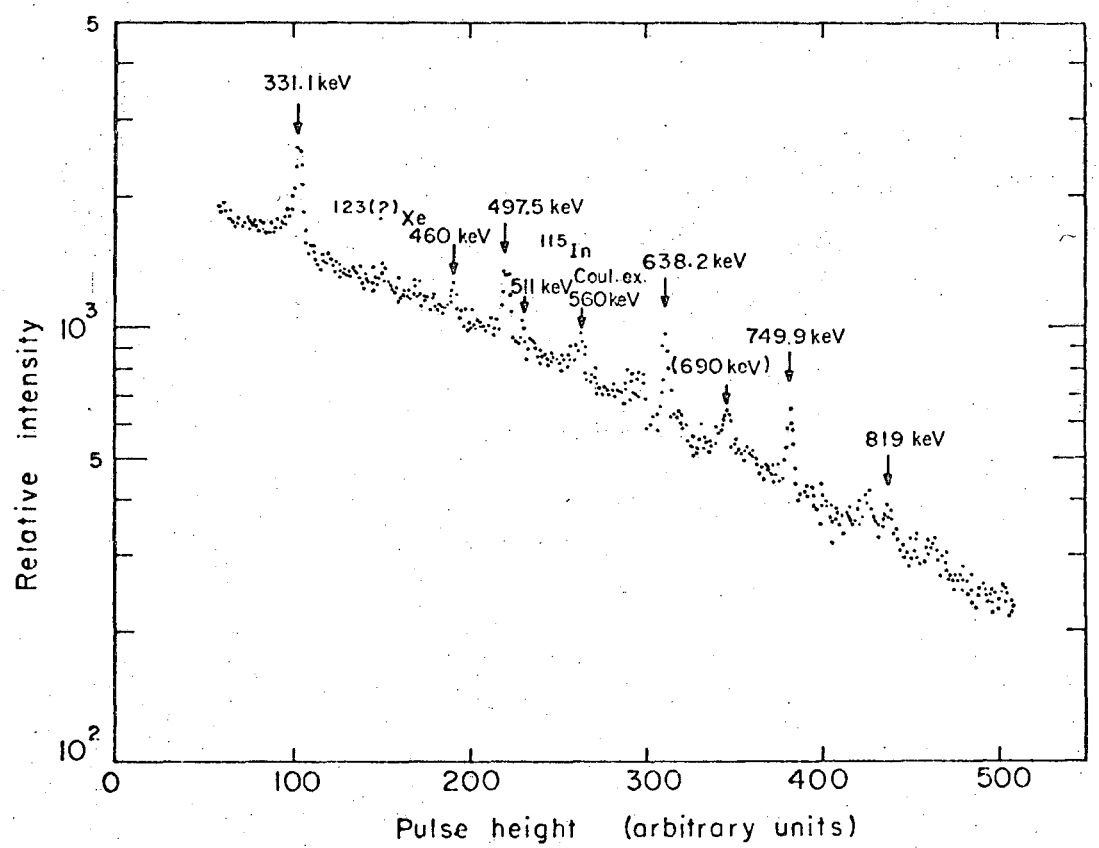

331.1 keV
123(?) Xe
460 keV
497.5 keV
115 In
511 keV
Coul. ex.
560 keV
638.2 keV
749.9 keV
(690 keV)
819 keV
Relative intensity
Pulse height (arbitrary units)
5
10^3
5
10^2
0
100
200
300
400
500

Fig. 8

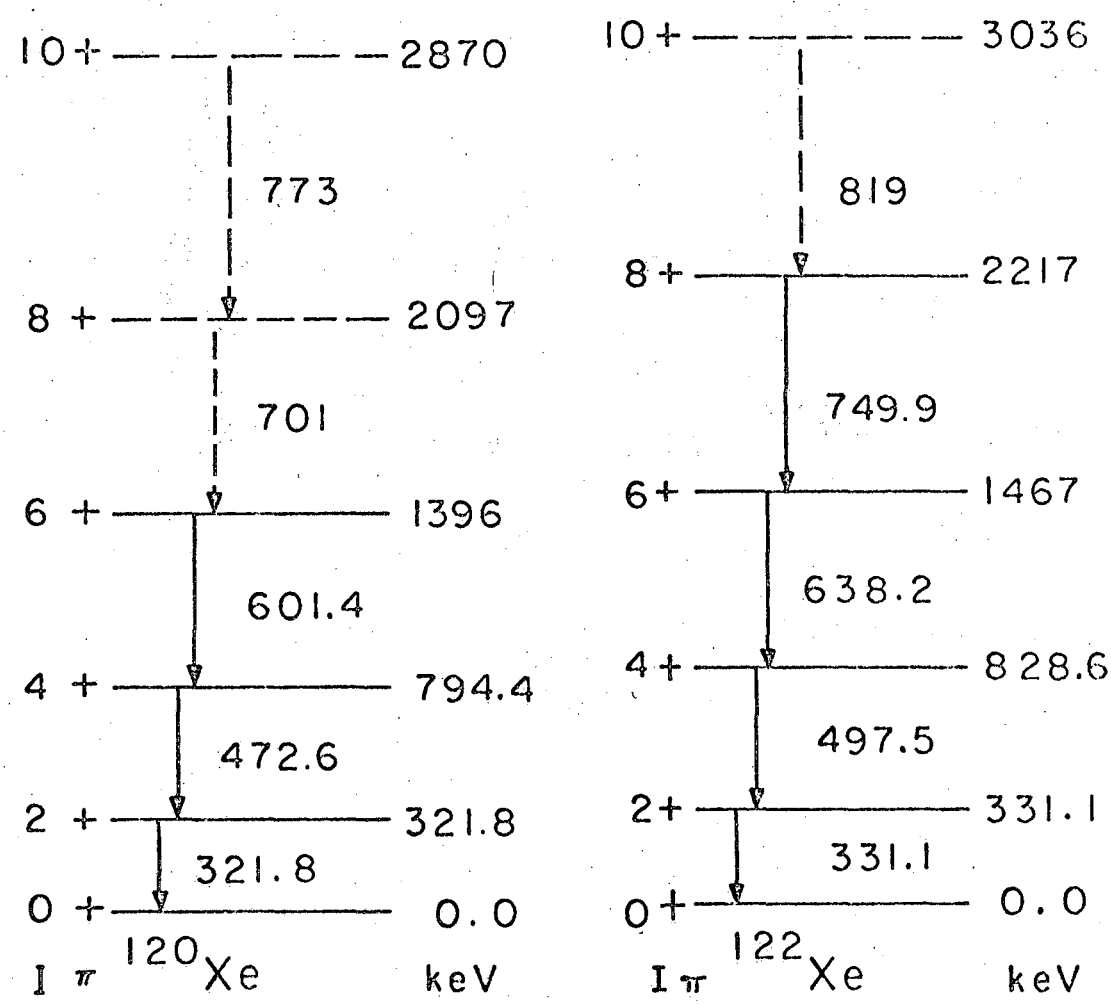

10+
2870
773
8 +
2097
701
6 +
1396
601.4
4 +
794.4
472.6
2 +
321.8
321.8
0 +
0.0
I π
120Xe
keV
10+
3036
819
8+
2217
749.9
6+
1467
638.2
4+
828.6
497.5
2+
331.1
331.1
0+
0.0
I π
122Xe
keV
MU-35632

Fig. 9

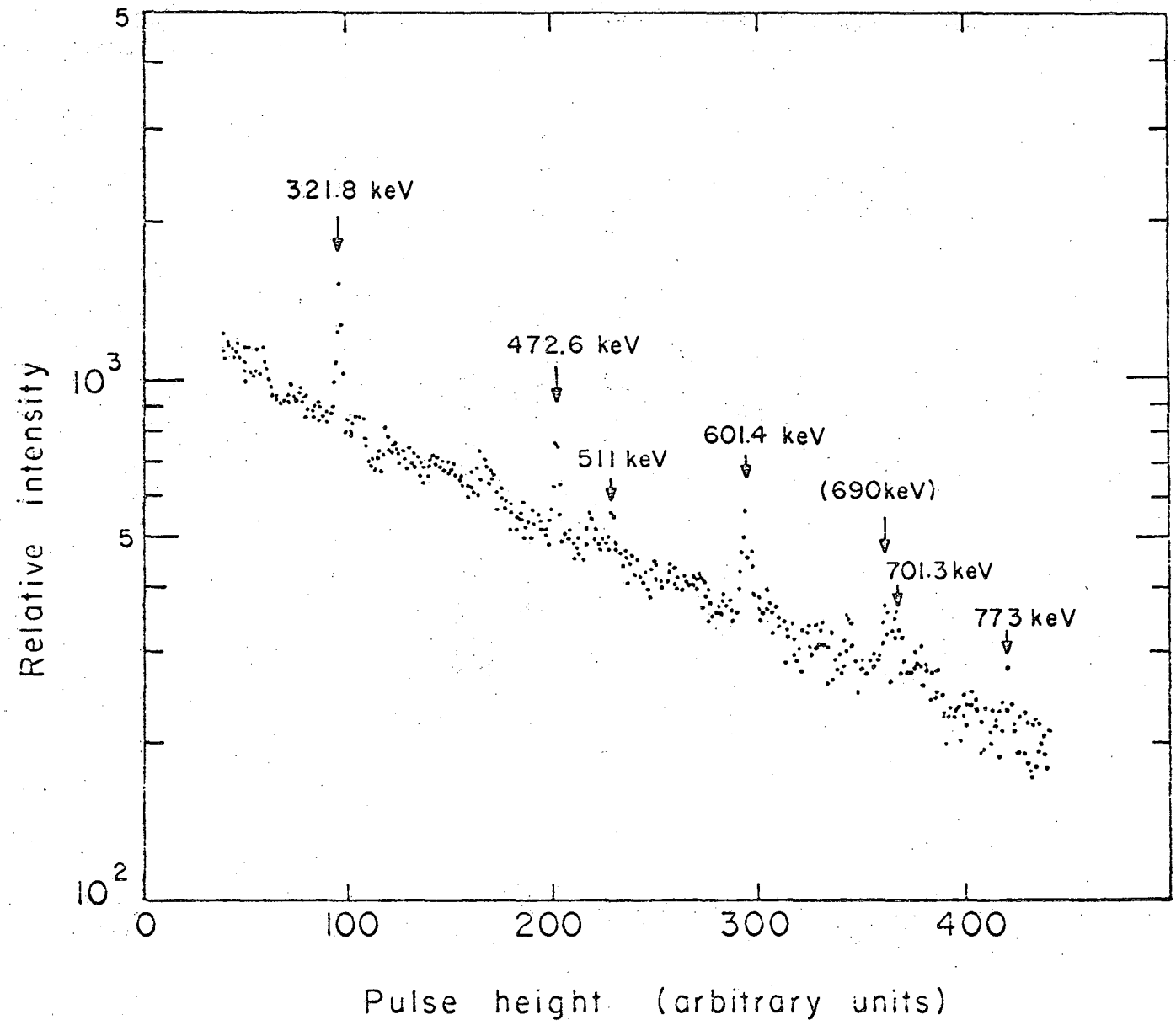
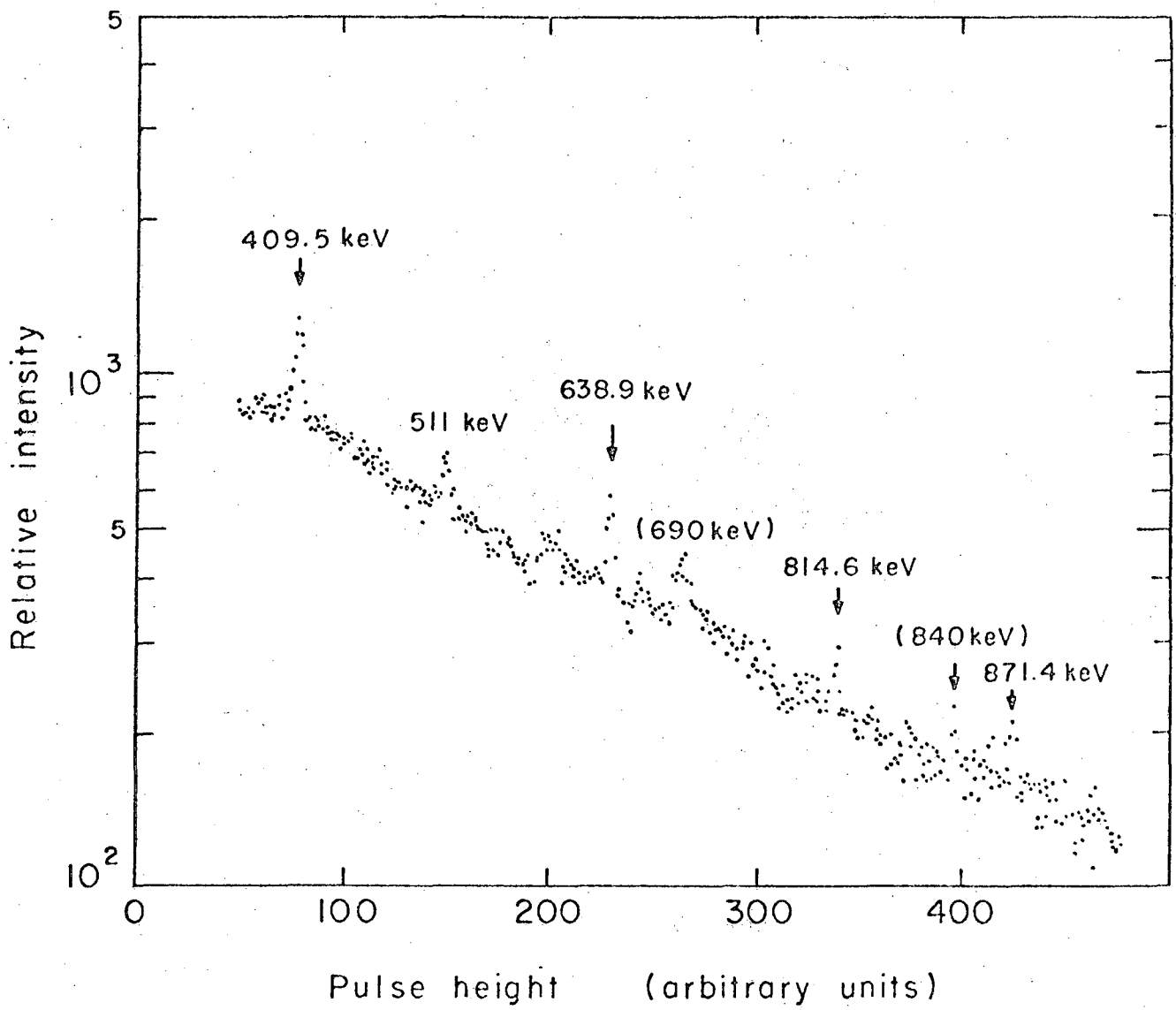


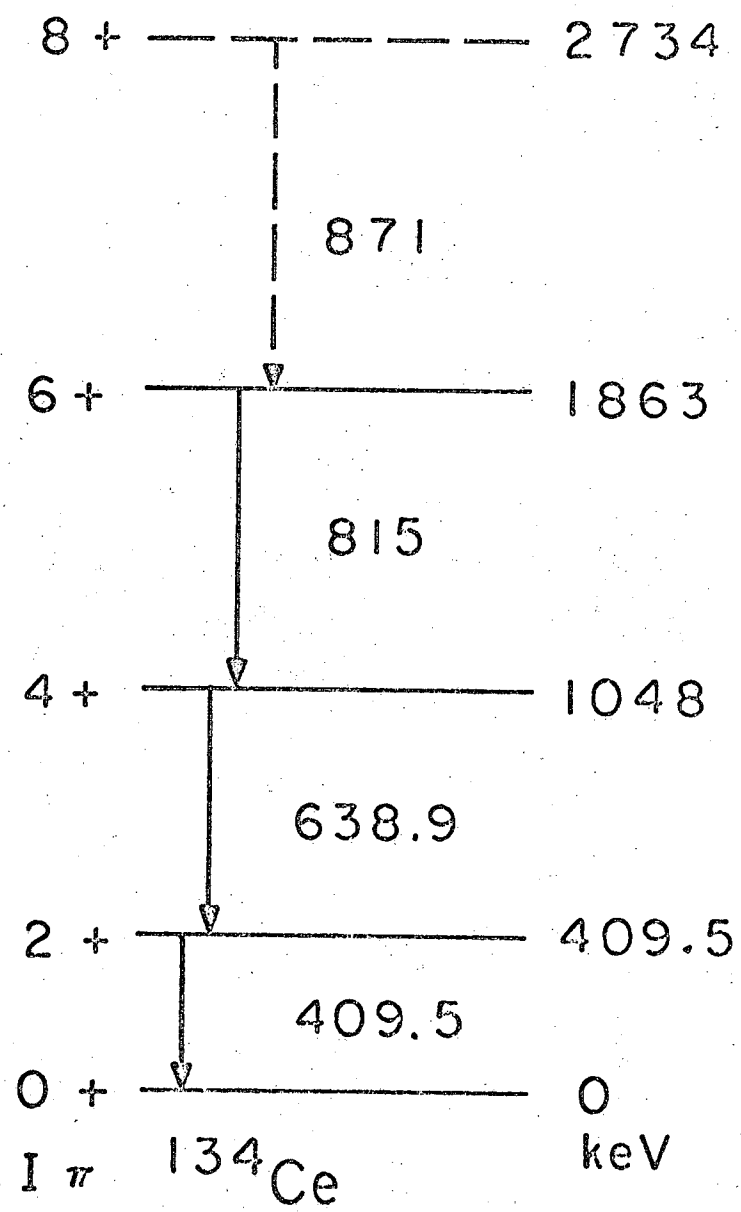
Fig. 10

MU-35636



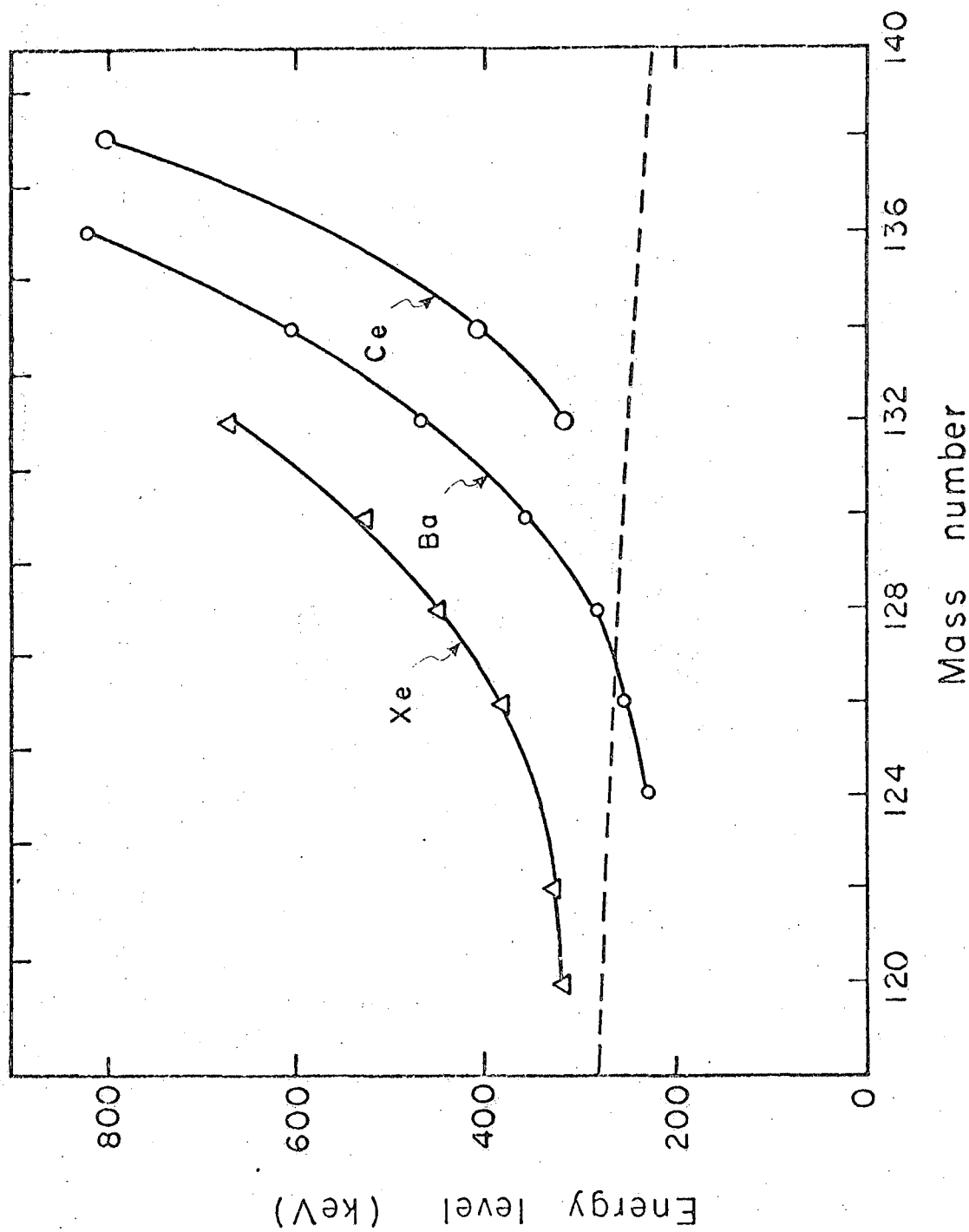
MU-35637

Fig. 11



MU-35631

Fig. 12



MU-35638

Fig. 13

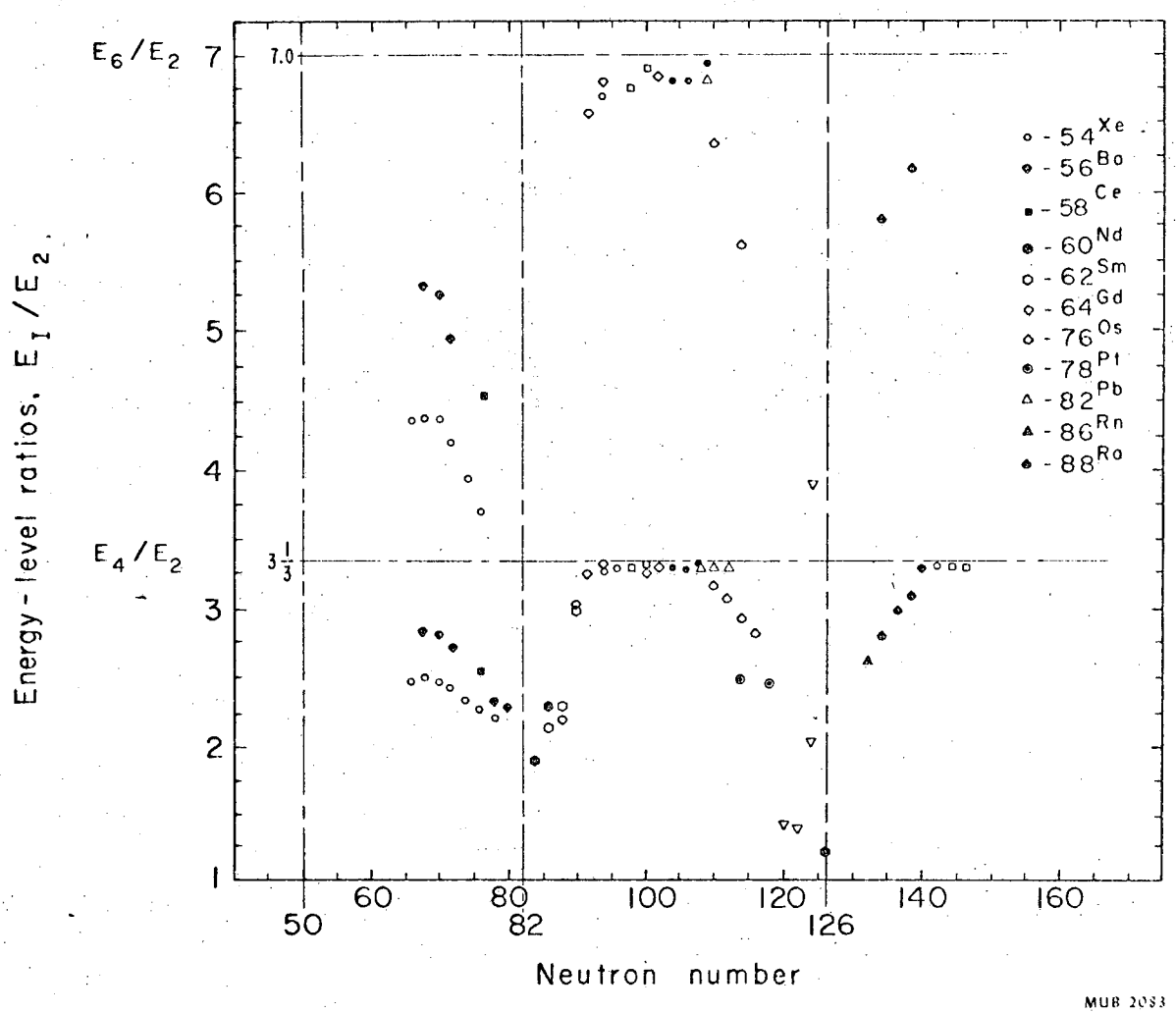
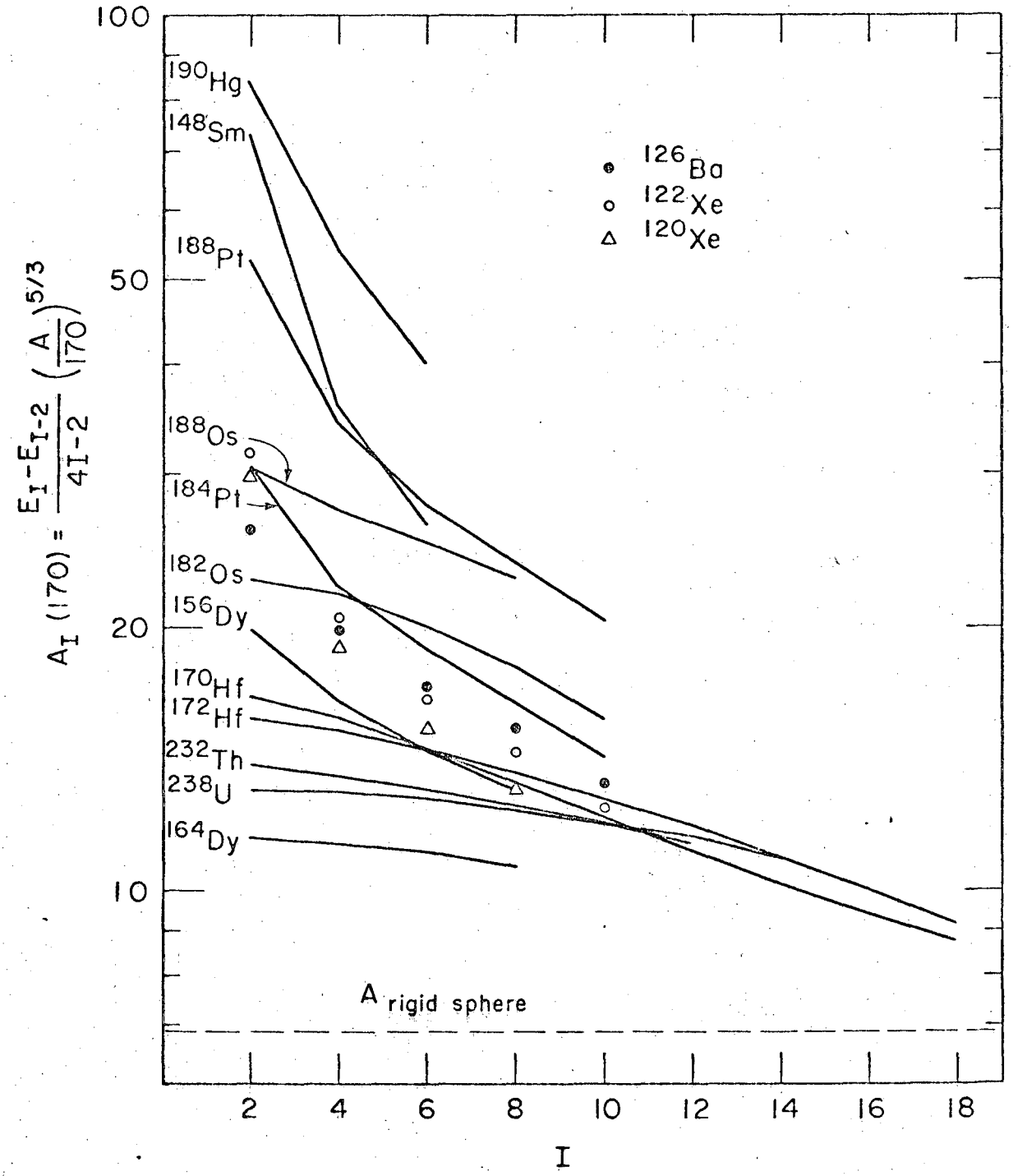

E6/E2
7.0
E4/E2
3 1/3
Energy-level ratios, EI/E2
Neutron number
50
60
80
82
100
120
126
140
160
1
2
3
4
5
6
7
- 54Xe
- 56Ba
- 58Ce
- 60Nd
- 62Sm
- 64Gd
- 76Os
- 78Pt
- 82Pb
- 86Rn
- 88Ra
MUB 2083

Fig. 14



MUB-10737

Fig. 15

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